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Andrea Sarzynski  
*University of Delaware*

George Galster  
*Wayne State University, GEORGE\_GALSTER@WAYNE.EDU*

Lisa Stack  
*Wayne State University, ap3434@wayne.edu*

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# Evolving United States metropolitan land use patterns

Andrea Sarzynski, George Galster, and Lisa Stack

**Abstract** We investigate spatial patterns of residential and non-residential land use for 257 U.S. metropolitan areas in 1990 and 2000, measured with 14 empirical indices. We find that metropolitan areas became denser during the 1990s but developed in more sprawl-like patterns across all other dimensions, on average. By far the largest changes in our land use metrics occurred in the realm of employment, which became more prevalent per unit of geographic area, but less spatially concentrated and further from the historical urban core, on average. Our exploratory factor analyses reveal that four factors summarize land use patterns in both years, and remained relatively stable across the two years: intensity, compactness, mixing, and core-dominance. Mean factor scores vary by metropolitan population, water proximity, type, and Census region. Improved measurement of metropolitan land use patterns can facilitate policy and planning decisions intended to minimize the most egregious aspects of urban sprawl.

**Keywords** Land use, sprawl

**Author Affiliations** Andrea Sarzynski, School of Public Policy and Administration, University of Delaware; George Galster, Department of Urban Studies and Planning, Wayne State University; Lisa Stack, Department of Sociology, Wayne State University.

## Introduction

The United States is overwhelmingly urban, with four of five Americans living within metropolitan areas as defined by the U.S. Census in 2000. Nevertheless, the urban experience varies dramatically, from newly emergent and rapidly growing suburban places such as Casa Grande, AZ, to mature urban powerhouses such as New York and Chicago, to declining rustbelt cities such as Charleston, WV. The urban experience also varies dramatically across time, as new economic realities and advances in communications and transportation technologies (among many other factors) begin to break down traditional urban arrangements

(Dear, 2011; Squires, 2002). New American metropolitan areas look and feel decidedly different from older American metropolitan areas, just as small American metropolitan areas look and feel decidedly different from large American metropolitan areas.

Despite this diversity of experience, the concept of urban sprawl has taken a particularly strong hold over our collective understanding of urban patterns and processes, such that sprawl is often presumed to be the dominant form and process of American urbanization today (Downs, 1999; Squires, 2002). Many scholars point to the declining average population density or to declining density-distance gradients as evidence of the predominance of urban sprawl in America (e.g., Fulton et al., 2001; Berry and Horton, 1970). These measurements intuitively capture our understanding of urban sprawl as a process: metropolitan areas are spreading out across space over time. A historical look at urban development reveals that most metropolitan areas have been spreading out across space for millennia (Bruegmann, 2005). Yet, this simple density measurement obscures the rich diversity of experience across metropolitan areas and ignores the fact that urban patterns and processes can be considerably different in two places with the same urban densities, or with the same rate of density change. Indeed, our understanding of the processes behind the spread of urban development across the landscape is constrained by the indicators we use to measure such change. We posit that an improved understanding of the changing spatial structure within metropolitan areas will also improve our understanding of the processes operating within metropolitan areas, and improve our understanding of which policy or planning tools might best be used to direct urban growth in coming years (Berry and Horton, 1970). We also posit that urbanization patterns and processes should be observed at the metropolitan scale, which incorporate central cities and their commuter-sheds. For this reason, we employ the phrase “sprawling” to depict the process of change over time but use the interchangeable phrases “metropolitan land use patterns” or “metropolitan spatial structure” to depict the pattern of urban development on the ground at any one point in time.

To improve our understanding of changing metropolitan spatial structure, we look to efforts that have conceptualized and measured such patterns using multiple dimensions, including but not limited to density. Illustrations of this multi-dimensional approach include Torrens and Alberti (2000), Galster et al. (2001), Ewing et al. (2002), Cutsinger et al.

(2005), Cutsinger and Galster (2006), Clifton et al. (2008), and Frenkel and Ashkenzai (2008). Prototype explorations indicate that the multiple dimensions are independent empirically (e.g., Cutsinger et al., 2005; Frenkel and Ashkenzai, 2008; Jaret et al., 2009) and have distinct predictive powers when it comes to many urban phenomena of interest. For example, cross-metropolitan correlations have been observed between: (1) health and density (Lopez and Hynes, 2003); (2) vehicle ownership and public transportation usage with density and centeredness (Ewing, Pendall, and Chen, 2003); (3) traffic congestion and density/continuity and housing centrality (Sarzynski et al., 2006); and (4) racial segregation and density/continuity and job compactness (Galster and Cutsinger, 2007). It follows that this multi-dimensional view holds important implications for planning and policy-making, as the achievement of particular goals will presumably necessitate the alteration of specific aspects of metropolitan land use.

Despite the conceptual and practical importance of multi-dimensional measures of metropolitan spatial patterns, some basic empirical foundations are missing. For instance, existing comparative research has mostly focused on measuring metropolitan spatial patterns at single points in time, and has not focused much attention on examining changes in patterns over time or whether cross-sectional multi-dimensional metrics can appropriately be adapted to examine these dynamics. It is this gap that we try to close with this paper. We build upon the multi-dimensional conceptualization and measurement of metropolitan land use patterns we originally developed and tested with a prototype sample of 50 large U.S. metropolitan areas as of 1990 [3 redacted citations]. Here we update and extend the coverage of our land use measurements to 257 U.S. metropolitan areas as of 1990 and 2000. This larger dataset allows us to replicate earlier analyses about the multi-dimensional nature of metropolitan land use, measured at a given point in time, as well as to probe the changes in metropolitan spatial structure during the 1990s.<sup>1</sup>

Specifically, this paper addresses descriptively three questions:

- How much, on average, have U.S. metropolitan areas changed

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<sup>1</sup> For other “sprawl” studies of the 1990s using residential metrics and conventional Census-derived boundaries, see Burchfield et al., 2006; Lopez and Hynes, 2003; Theobald, 2001.

from 1990 to 2000 in terms of indicators of seven conceptual dimensions of land use previously established in the literature: density, concentration, centrality, continuity, proximity, mixed-use, and nuclearity?

- Do these indicators collapse into more parsimonious summary factors of land use and are these factors stable between 1990 and 2000?
- Do the land use patterns along these summary factors vary according to characteristics of the metropolitan area?

Our analysis contributes to geographical scholarship by investigating the dynamics of metropolitan land use change using multi-dimensional metrics consistently measured for two points in time across the largest sample of U.S. metropolitan areas to date that have been appropriately bounded for sprawl measurement. Our paper begins with a summary of methods we previously developed for measuring metropolitan land use patterns [citations redacted]; details are relegated to appendices. We then address the three research questions described above, and close with future research directions.

## **Methodological Overview**

Measurement of metropolitan land use patterns is plagued by several methodological concerns. Chief among the concerns are selecting an appropriate geography at which to measure metropolitan land use patterns and specifying the best indices that capture the complexity and multidimensionality of metropolitan land use patterns. We outline our approach in the following sections.

### **The Geographic Area Employed as Unit of Analysis**

In this study we employ a spatial unit of analysis of our own formulation that we label the “extended urban area” (EUA). The EUA includes the Census-designated Urbanized Area (typically defined as contiguous blocks having a population density of at least 1,000 persons per square mile) plus additional areas that are functionally related to this core. We specify these as areas with moderate commuting to the Urbanized Area (30 percent or more households) and with suburban housing densities (60 units per square mile or 10 acres per unit). The commuting threshold

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derives from the Economic Research Service's Rural-Urban Commuting Area (RUCA) codes for "high commuting" to an Urbanized Area. The housing unit threshold is consistent with other classifications of suburban development, such as Theobald (2001).

In an earlier publication [citation redacted] we carefully explored the features of this formulation and concluded that the EUA reasonably bounds the relevant area for measuring metropolitan land use patterns and is superior to Census-defined Urbanized Areas or Metropolitan Statistical Areas. Las Vegas illustrates the problem of over-bounding with MSAs: our EUA definition captures nearly 88 percent of the MSA population in 2000 residing on only 1.1 percent of the Census-defined Metropolitan land area. Bellingham, WA illustrates the problem of under-bounding with UAs: our EUA definition covers 547% more land area than the UA definition in 2000, capturing 45% more population. Thus, our EUA selection criteria combine the most relevant characteristic of the Census urbanized area definition (urban density) with the most relevant characteristic of the Census metropolitan statistical area definition (commuting) to minimize under- and over- bounding of the study area.<sup>2</sup>

### Data Collection and Initial Processing

In this study we utilized multiple data sources, managed within a geographic information system (GIS). Each data layer was converted from a polygon layer to a 500m x 500m raster layer, allowing us to apportion attributes of each layer to individual cells, which became the units of analysis for computing land use indices.

We began by operationalizing EUAs for 331 Metropolitan Statistical Areas in the U.S. We used the December 1999 boundary definitions of Metropolitan Statistical Areas for both 1990 and 2000 indices. We obtained for each metro's Urbanized Area its 1990 and 2000 Census-defined boundaries, with the former redefined using the 2000 Urbanized Area selection criteria so we could make direct comparisons across years.<sup>3</sup> We next added census tract boundaries for both 1990 and 2000 and merged rural/ urban commuting area (RUCA) data from the Economic Research Service (ERS) at the U.S. Department of Agriculture. The RUCA data

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<sup>2</sup> For a thorough discussion of the issue of the appropriate scale of a metropolitan region, see Dahmann and Fitzsimmons (1995) and Adams, Van Drasek and Phillips (1999).

<sup>3</sup> Personal communication, Michael Ratcliffe, U.S. Census Bureau, September 21, 2009.

were used to identify census tracts where at least 30 percent of its residents commuted to the Urbanized Area, denoted as “high commuting” by ERS. Finally, we added block groups and their associated housing and population counts and apportioned them to the 500m x 500m cells, assuming that population or housing were equally distributed across cells within the block groups, once their areas had been adjusted for “undevelopable” land; see Appendix 1 for details. These data permitted us to designate non-Urbanized Area cells that met commuting and housing unit density thresholds to be included in our EUA.<sup>4</sup>

We next added the number of workers in each grid cell for both 1990 and 2000, employing data on place of work from the Census Transportation Planning Package (CTPP) maintained by the Bureau of Transportation Statistics. Merging in these data across geography took considerable effort; see Appendix 2 for details.<sup>5</sup>

Finally, we identified the physical addresses of city halls or county seats for the central cities named within the metropolitan area definitions. For suburban metropolitan areas of multiple counties, such as Nassau--Suffolk, NY or Bergen--Passaic, NJ, we identified the location of the administrative offices for the county seat. We excluded several of the city halls or county seats that were located in very low density areas with few nearby EUA cells. We then calculated the Euclidean distance from each cell in the EUA to these points, using the nearest point in metropolitan areas with multiple points. The distances were used in the centrality calculations, as discussed below.

## Sample

The analysis reported here includes 257 Metropolitan Statistical Areas that had complete housing and employment data, and met the EUA

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<sup>4</sup> Because our grid cells are smaller than a square mile, we calculated a kernel density function for each grid cell that compiled housing units up to a mile in each direction, which smoothes the density surface to avoid small breaks. Thus, the EUA boundaries included a contiguous area surrounding the UA and adjacent cells meeting our selection criteria, plus included detached areas surrounding the core but still meeting the selection criteria, such as for bedroom communities.

<sup>5</sup> Worker location was coded by the Census Bureau for the respondent's primary employment location, even if respondents had multiple jobs. Thus, while we use the shorthand “jobs” throughout the document, in reality the data are for workers that were surveyed by the Census Bureau and likely undercount total jobs in some locations.



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definitional criteria, for both 1990 and 2000. The sample EUAs are located throughout the country, ranging in population size from just over 50,000 (Sharon, PA; Glens Falls, NY; Pittsfield, MA) to nearly 10 million residents (New York; Los Angeles) in 2000. The sample includes the most-populous Metropolitan Statistical Areas in 1990 and 2000, excepting Atlanta, Minneapolis-St. Paul, and St. Louis due to missing 1990 employment data for at least one of their outlying counties. Together, the sample EUAs housed 162 million residents in 2000 and comprised 57 percent of the United States' population.

### Measuring Metropolitan Land Use Patterns

Our previous work [redacted] posited that the pattern of metropolitan land use could be measured along seven conceptually distinct dimensions: density, continuity, concentration, exposure, centrality, proximity, and (mono) nuclearity. Here we review briefly these dimensions and the land use metrics used for this analysis.<sup>6</sup> Where appropriate we use multiple metrics for each dimension and corresponding metrics for both residential and employment patterns, as our previous work illustrated that employment and housing patterns diverge in important ways (confirmed by Burchfield et al., 2006; Jaret et al., 2009). We focus on housing patterns for residential metrics, presuming that housing is a better indicator of on-the-ground changes in urban development than population (Theobald, 2001). Each metric is scaled such that larger values indicate more of each dimension and less "sprawling" patterns; for detailed formulae, see Appendix 3.<sup>7</sup>

**Density**      The degree to which the EUA is intensively developed.

- a. Housing density: the average number of housing units per grid cell in the EUA.
- b. Job density: the average number of jobs per grid cell in the EUA.
- c. Peripheral density: the share of the EUA that is classified as the

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<sup>6</sup> We made several changes in how we operationalized measurement of metropolitan land use patterns compared to our prototype work with 50 EUAs [redacted]. Thus, readers should not compare land use indices computed as part of that earlier work with those reported here.

<sup>7</sup> For complete descriptions and visual representations of each conceptual dimension please see (Redacted). See appendix 3 for measurement equations.

Urbanized Area (UA) by the U.S. Census Bureau.<sup>8</sup>

**Continuity** The degree to which developable land has been developed (for any urban use) in an unbroken fashion throughout the metropolitan area. We operationalized this as the percentage of grid cells within the EUA in which 50 percent or more of the land that could be developed has been developed, adjusting for “undevelopable land.”<sup>9</sup>

**Concentration** The degree to which housing units and jobs are located disproportionately in a few cells within the EUA.<sup>10</sup>

- a. Housing concentration: the percentage of housing units that would need to shift cells to produce an even distribution of housing units across cells in the EUA.
- b. Job concentration: the percentage of jobs that would need to shift cells to produce an even distribution of jobs across cells in the EUA.

**Centrality** The degree to which housing units and jobs are located nearer to the core of the EUA. We defined the core of the EUA as the location of city hall(s) for each Metropolitan Statistical Area, as described above. We measured the distance between each grid cell centroid in the EUA and its nearest city hall, weighted by the number of housing units or jobs in each cell. We standardized this weighted average distance by the average distance to city hall from the grid cells comprising the EUA, so as not to inevitably specify larger EUAs as less centralized.

- a. Housing centrality: the ratio of the average distance to city hall of grid cells comprising the EUA to the average distance to city hall of a housing unit within the EUA.
- b. Job centrality: the ratio of the average distance to city hall of grid

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<sup>8</sup> For 1990, we used the urbanized area boundaries that had been redefined using the same selection criteria used to define the 2000 urbanized areas, allowing appropriate comparisons over time.

<sup>9</sup> Our previous work identified ice, water, and wetlands as three classes of land cover that should be excluded as “undevelopable” land for the purposes of measuring land use patterns (redacted). Here, we clipped the block group boundaries to its “developable” land area using data on surface water and wetlands from the U.S. Geological Survey (USGS), as of 2001. The surface water data layer includes oceans, bays, lakes, reservoirs, rivers, canals, streams, glaciers, and swamp or marsh areas.

<sup>10</sup> This measure is equivalent to a Dissimilarity index often employed in segregation research.

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cells comprising the EUA to the average distance to city hall of a job within the EUA.

**Proximity** The degree to which housing units, jobs or housing unit/job pairs are close to each other across the EUA, relative to the land area of the EUA. Like centrality, proximity utilizes weighted averages of the distance between jobs, housing units, or job/housing unit pairs across all cells (with all houses and jobs assumed to be located at their respective cell's centroid) comprising the EUA so that jobs and housing units on the urban fringe (and, therefore, less proximate to clusters of jobs and housing units near the urban core) do not overly influence estimates. The standardized proximity index adjusts for metropolitan area size in a similar manner as centrality. For feasibility of computing proximity, we aggregated the information to one-square-mile grid cells.

- a. Housing proximity: the ratio of the average distance among centroids of square-mile cells in the EUA to the weighted average distance among housing units in the EUA.
- b. Job proximity: the ratio of the average distance among centroids of square-mile cells in the EUA to the weighted average distance among jobs in the EUA.
- c. Jobs to Housing proximity: the ratio of the average distance among centroids of square-mile cells in the EUA to the weighted average distance among jobs and housing units in the EUA.

**Mixed-Use** The degree to which housing units and jobs are located in the same grid cell, on average, across the EUA.

- a. Exposure of jobs to housing: the average number of housing units in the same EUA cell where there are jobs.
- b. Exposure of housing to jobs: the average number of jobs in the same EUA cell where there are housing units.

**Nuclearity** The degree to which jobs within a EUA are disproportionately located in the core, as opposed to a multi-centric fashion. We operationalize mono-nuclearity as the ratio of jobs in the core nucleus (Central Business District) to jobs in all other nuclei; CBD is operationalized as grid cells containing or adjacent to the cell containing the city hall of the largest municipality defining the EUA. We tested different approaches and ultimately defined job nuclei as clusters of cells where the average job density (smoothed across square miles) was more

than four standard deviations above the EUA mean.<sup>11</sup> This criterion ensured that we obtained only nuclei with regionally significant employment concentrations for each EUA, as we might expect from “edge city” type clusters (Garreau, 1991).

### Analytical Methods

This paper explores the multi-dimensional variation and change in U.S. metropolitan land use patterns during the 1990s. We first examine the change in metropolitan land use patterns over time, using paired t-tests and Spearman rank correlations. We next employ exploratory factor analysis to determine whether our 14 indices collapse into a more parsimonious set of uncorrelated factors, and whether the underlying data structure is stable from 1990 to 2000. Two separate analyses are performed on the 14 indices for 1990 and 2000. Four criteria are used to retain the appropriate number of factors in each year: eigenvalue, scree plot, variance, and residuals analysis (Mertler & Vannatta, 2002).<sup>12</sup> We also examine with difference-in-means analysis whether the factor scores varied across EUAs according to a few key characteristics of their metropolitan area: EUA population size class ( $\leq 100,000$ ; 100,001-500,000; 500,001-1 million;  $>1$  million), coastal location, metropolitan type (MSA or PMSA), and Census region.<sup>13</sup> Further analysis of the EUAs in 2000 is presented in the companion article in this issue [citation redacted].

The analysis presented here does not include the year 2010 because comparable small-area employment data for 2010 have not yet been released for the entire U.S., and we are reluctant to analyze metropolitan

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<sup>11</sup> Two areas did not have any nuclei that met the four standard deviation criterion in 1990, although they did have one employment nucleus each in 2000 (Dover, DE, and Grand Forks, ND). To retain these areas in our sample, we imputed a value of 1 for nuclearity in 1990.

<sup>12</sup> Factors with eigenvalues less than one were only retained if the solution coincides closely to other criteria. Factors with eigenvalues before the first level occurs in the scree plot were retained. Generally, retained factors should account for at least 70 percent of the total variability. Finally, the reproduced correlations compared to the observed correlations should only have a small percentage of residuals greater than the absolute value of 0.05 to be selected for the most appropriate solution.

<sup>13</sup> These findings were confirmed using ANOVA tests using the Scheffe adjustment for groups of unequal variance. Only statistically significant results are reported. The results are presented for the year 2000, although similar patterns are evident for both years; detailed results are available from the authors.

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land use patterns based only on residential metrics. Even without 2010 data, we believe that this paper and its companion are important because they significantly expand the analysis of metropolitan land use patterns for 311 areas using both residential- and employment-based metrics. No other study has prepared indices as powerful and revealing as ours, primarily because they are so challenging to compute. Yet, this is precisely what makes our contributions unique and important even when they do not employ as current data as we might wish. Future analysis will examine the changes from 1990-2010 once the small-area employment data have been released.

## Results and Discussion

The following section addresses our three research questions regarding: (1) the change in metropolitan land use patterns from 1990 to 2000 across multiple land use metrics; (2) whether combinations of metrics collapse into distinctive and stable land use dimensions; and (3) how the factor scores vary by key characteristics of the metropolitan area. Before turning to the answers to these questions, the basic descriptive statistics of our 14 indices are presented in Table 1.<sup>14</sup> Although we leave it to the interested reader to probe more detailed patterns, suffice it to note here that we observe substantial cross-sectional variation in both years, confirming the divergence of urban experiences across metropolitan areas in the United States.

**Table 1.** Descriptive Statistics of Metropolitan Land Use Indices for 1990 and 2000

Index	Mean	Std.	Minimum	Maximum
<b>1990 Values:</b>				
Housing Density	545.52	420.73	172.70	4751.68
Job Density	617.61	502.53	108.20	4904.04
Peripheral Density	0.44	0.13	0.14	0.88
Continuity	0.41	0.16	0.10	0.97
Housing Concentration	0.52	0.05	0.34	0.69
Job Concentration	0.72	0.08	0.46	0.92
Housing Centrality	1.55	0.24	0.94	2.41

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<sup>14</sup> The density and exposure values were significantly and positively skewed across the entire sample in both 1990 and 2000. A log transformation was performed on these four indices.

Job Centrality	2.50	0.88	1.01	5.55
Housing Unit Proximity	1.55	0.32	0.84	3.26
Job Proximity	2.40	0.94	0.83	5.50
Housing Unit to Job Proximity	1.79	0.43	0.82	3.55
Exposure of Jobs to Housing Units	175.53	158.07	38.41	2207.11
Exposure of Housing Units to Jobs	199.00	198.59	42.85	2706.05
Nuclearity	0.89	0.19	0.00	1.00
<b>2000 Values:</b>				
Housing Density	551.31	462.95	187.12	5220.64
Job Density	667.68	552.27	181.33	5197.04
Peripheral Density	0.45	0.14	0.16	0.97
Continuity	0.38	0.15	0.09	0.97
Housing Concentration	0.51	0.05	0.32	0.69
Job Concentration	0.64	0.06	0.41	0.77
Housing Centrality	1.52	0.22	0.93	2.32
Job Centrality	1.93	0.43	0.93	3.87
Housing Unit Proximity	1.50	0.27	0.96	2.57
Job Proximity	1.86	0.52	0.95	4.47
Housing Unit to Job Proximity	1.63	0.34	0.94	3.04
Exposure of Jobs to Housing Units	158.67	162.70	45.54	2306.54
Exposure of Housing Units to Jobs	193.94	200.13	46.12	2666.30
Nuclearity	0.86	0.18	0.28	1.00

**Note:** N=257 extended urban areas.

### Change In Metropolitan Land Use Patterns, 1990-2000

Conventional wisdom has it that American metropolitan areas are sprawling, no matter how it is measured. If this wisdom were true, we should see declining values across our seven land use dimensions and 14 indices during the 1990s, illustrating that EUAs were becoming less dense, less continuously developed, less centralized, with less proximate development, less mixing of land uses, and that employment was becoming less core-dominant as alternative job centers emerged.

A comparison of means illustrates the geographic evolution of EUAs during the 1990s that is more complex than this simplistic conventional wisdom (Table 2). Three indicators—all related to various aspects of density—exhibited increases in mean values over the decade: housing density, job density, and peripheral density (although the change in housing density was not significant). The remaining 11 indicators all

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exhibited significant decreases in mean values over the decade, consistent with conventional wisdom.<sup>15</sup>

**Table 2.** Change in Mean Values of Metropolitan Land Use Indices, 1990-2000

Index	1990 Mean	2000 Mean	Change Mean <sup>#</sup>	Percentage Change Mean	# of EUAs w/ Declining Values (Sprawling)
Housing Density	545.52	551.31	5.80	1.10	136
Job Density	617.61	667.68	50.06***	8.10	84
Peripheral Density	0.44	0.45	0.01***	2.30	105
Continuity	0.41	0.38	-0.03***	-7.30	194
Housing Concentration	0.52	0.51	-0.01***	-1.90	181
Job Concentration	0.72	0.64	-0.08***	-11.10	238
Housing Centrality	1.55	1.52	-0.03***	-1.90	150
Job Centrality	2.50	1.93	-0.58***	-22.80	231
Housing Unit Proximity	1.55	1.50	-0.05***	-3.20	174
Job Proximity	2.40	1.86	-0.54***	-22.50	212
Housing Unit to Job Proximity	1.79	1.63	-0.16***	-8.90	211
Exposure of Jobs to Housing Units	175.53	158.67	-16.86***	-9.60	201
Exposure of Housing Units to Jobs	199.00	193.94	-5.06*	-2.50	149
Nuclearity	0.89	0.86	-0.03**	-3.40	114

**Notes:** N = 257 extended urban areas (EUAs); # statistical significance of mean change measured by a paired t-test (2-sided); \* p<0.1, \*\* p<0.05, \*\*\*p<0.001.

By far the most dramatic changes in some EUAs were related to the location of employment. On average, our EUAs grew more employment-dense (over seven percent) with the economic expansion during the 1990s, but the concentration of these jobs fell almost 11 percent and their proximity to each other and their proximity to the central business district both fell over 22 percent, on average, indicating the relative strength of dispersed, peripheral job creation during the 1990s. By contrast, changes in the spatial patterns of metropolitan population and housing

<sup>15</sup> The large change in mean job centrality may be a result of missing jobs data for 1990 in some outer counties of some EUAs, which may be unduly influencing job centrality scores. Even so, the changes in job centrality among the ones with complete jobs data exhibit similar declining trends in centrality, suggesting that the finding is not entirely the result of missing jobs data.

development were modest during the 1990s, on average, with an insignificant change in mean housing densities. These results highlight the importance of including both residential and employment metrics when characterizing metropolitan land use patterns.

**Table 3.** Rank-Order Correlations between 1990 and 2000 Metropolitan Land Use Indices

Index	Spearman's rho
Housing Density	0.95
Job Density	0.91
Peripheral Density	0.85
Continuity	0.94
Housing Concentration	0.90
Job Concentration	0.60
Housing Centrality	0.86
Job Centrality	0.63
Housing Unit Proximity	0.84
Job Proximity	0.69
Housing Unit to Job Proximity	0.83
Exposure of Jobs to Housing Units	0.89
Exposure of Housing Units to Jobs	0.90
Nuclearity	0.47

**Notes:** N=257; correlation is statistically significant at the 0.001 level (2-tailed) for all 14 metrics.

This theme is echoed when we consider how the inter-metropolitan rankings for the various land use dimensions shifted during the decade (Table 3). The rankings of EUAs for the density, continuity, and mixed-use indices were quite stable from 1990 to 2000, as indicated by the very high Spearman's rank-order correlations. The rankings for housing concentration, housing centrality, housing-housing proximity, and housing-job proximity were also stable. The rankings for nuclearity and job concentration, especially, as well as job centrality and job proximity were less stable between the two years, suggesting less consistent changes in the spatial distribution of jobs within EUAs during the decade. Some of the changes in job patterns may reflect better employment data for 2000 than for 1990, as discussed in Appendix 2, although we expect much of



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the variation has to do with the shifting distribution of economic activity among metropolitan regions within the U.S. and abroad.

The majority of “urban sprawl” measurements use some version of density to compare the pattern or process of sprawl across metropolitan areas. Metropolitan areas with low density (as a pattern) or with declining density over time (as a process) are usually depicted as sprawling. Our analysis finds that the mean employment density and mean peripheral density both increased during the 1990s, even while the mean values for the other metrics declined during the decade. As noted in Table 2, 121 EUAs (47 percent) experienced steady or increasing housing density, 173 EUAs (66 percent) experienced steady or increasing employment density, and 152 EUAs (59 percent) experienced steady or increasing peripheral density during the 1990s. These results indicate a sizable cluster of EUAs that were undoubtedly densifying during the 1990s, contrary to conventional wisdom. These densifying EUAs were more likely to be located in coastal areas, in larger urban agglomerations (i.e., PMSAs), and be facing stronger population growth pressures (results available upon request). Examples include Seattle, Fort Lauderdale, and Atlantic City EUAs. Lopez and Hynes (2003) also found a notable group of metropolitan areas (30 percent; 98 of 330 areas) that experienced steady or increased concentration of population in high-density census tracts during the 1990s, leading them to conclude that “population growth ... may have pushed some of these metropolitan areas into more dense configurations” (p.341). Differences in mean values illustrate general changes across the full sample during the ten-year study period. Yet, these mean changes mask changes in individual EUAs, which in some places were dramatic. Without performing an exhaustive review, we highlight here several of the apparently most-sprawling and least-sprawling EUAs in our sample, as measured across multiple dimensions.

The most apparently “sprawling” areas in our sample were EUAs that experienced declining values across all 14 indices during the 1990s. This group included two EUAs in the midwest (Appleton-Oshkosh-Neenah, WI; Des Moines, IA) and five EUAs in the south (Albany, GA; Fayetteville-Springdale-Rogers, AR; Fort Smith, AR; Parkersburg-Marietta, WV; Pine Bluff, AR). Another one EUA in the midwest (Champaign-Urbana, IL), one EUA in the northeast (Springfield, MA), and three EUAs in the south (Columbia, SC; Gadsden, AL; Goldsboro, NC) had declining or steady values across all 14 indices. These 12 areas were all relatively

small in population size, with only the largest (Springfield) having a population of more than 500,000 in 2000. All of these apparently “sprawling” EUAs were also experiencing population and job growth during the 1990s, with the exception of a small population decline (but employment increase) in the Pine Bluff EUA.

The Fayetteville-Springdale-Rogers, AR EUA stands out for its rapid outward expansion during the 1990s, resulting in a dramatic decline in peripheral density and mono-nuclearity. This change presumably reflects strong suburban growth pressures and a marked change in the amount of land meeting the EUA designation criteria from 1990 to 2000. In Fayetteville, the Census-defined urbanized area land more than doubled and additional cells meeting the housing density + commuting thresholds increased approximately 350 percent during the 1990s. Like Fayetteville, many EUAs experiencing strong growth pressures during the 1990s also experienced declining housing density, peripheral density, housing-jobs proximity, and nuclearity.

None of the EUAs experienced increases (or no change) in all of the metrics during the 1990s, as would suggest a “compacting” metropolitan structure. Yet, almost all EUAs had increasing values on at least one of the 14 metrics. San Diego, CA experienced increasing values across all indices excepting peripheral density; Dover, DE experienced increasing values across all indices excepting peripheral density and job concentration; and San Luis Obispo-Atascadero-Paso Robles, CA and Stockton-Lodi, CA experienced increasing values across all indices excepting housing concentration, housing proximity, and mono-nuclearity. Altogether, 51 EUAs experienced increased values in at least half of the land use indices, with 19 of these EUAs from the western U.S. EUAs in the western U.S. were substantially more likely to see increased values on the land use indices than EUAs in any of the other regions, as were coastal EUAs located throughout the country (results available upon request). These results confirm that metropolitan areas in arid and topographically constrained areas may be less likely to sprawl than metropolitan areas not facing such climatic and geographic constraints (Fulton et al., 2001; Lang, 2002).

### **Commonalities Among Metropolitan Land Use Indices**

The previous section reviewed the changing land use patterns among our sample of U.S. metropolitan areas during the 1990s. While most all areas

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experienced changing patterns, substantial diversity exists among the pattern of change across our 14 metrics. Here we consider the extent to which our 14 land use indices are interrelated and may be collapsed into a smaller number of summary factors depicting U.S. metropolitan land use patterns.

As expected, indices measured for the same conceptual dimension exhibit high degrees of comparability in both 1990 and 2000; see Appendix D. For instance, areas with high housing density also tended to have high jobs density. The exception is the lack of correlation between the housing concentration and job concentration in 1990 (although modestly correlated in 2000).

Of more interest, the density, continuity, and mixed-use indices are positively correlated with one another, with the magnitude of the correlations increasing from 1990 to 2000. The job concentration index is negatively associated with the density, continuity, and mixed-use indices. The centrality and proximity indices are all moderately and positively associated. By contrast, the mono-nuclearity index is only modestly correlated with the other indices. Taken together, the 14 indices appear interrelated but in a complex manner, confirming the diversity of urban experience across U.S. metropolitan areas.

We next perform exploratory factor analysis, a data reduction tool to isolate summary “factors” based on relationships between indices. After experimenting with solutions containing four to six factors, we found that the most parsimonious solution in each year involved four factors (Tables 4 and 5). The four retained factors cumulatively explained a robust 81 percent of the variation in the original 14 indices in 1990, while the four retained factors explained 84 percent of the variation in 2000. We also found remarkable stability in the factorial ecology across the two years, suggesting that the underlying structure of metropolitan land use patterns—the interrelationships among indicators—did not change appreciably during the 1990s, even though in some metropolitan areas the values of these indicators changed dramatically.<sup>16</sup>

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<sup>16</sup> We also experimented with factor analysis of the absolute change in indices for 1990-2000. We found that the results were difficult to interpret as the units are different across the indices and changes depend on starting values. We explore other ways to analyze dynamics and drivers of land use change in an upcoming paper.

**Table 4.** Exploratory Factor Analysis Results for 1990

	Component			
<b>Summary Statistics</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
Initial Eigenvalue	5.13	3.77	1.42	1.03
Percent of Variance Explained	27.00	27.00	10.00	7.00
Rotation Eigenvalue	3.70	3.51	2.99	1.16
Percent of Variance Explained	26.00	25.00	21.00	8.00
<b>Rotated Factor Loadings</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
Housing Density*	0.78	-0.07	0.56	-0.06
Job Density*	0.74	-0.03	0.58	0.13
Peripheral Density	0.89	-0.16	0.10	0.01
Continuity	0.84	-0.05	0.04	-0.30
Housing Concentration	-0.06	0.20	0.73	0.30
Job Concentration	-0.74	0.27	-0.08	-0.41
Housing Centrality	-0.09	0.67	0.27	0.36
Job Centrality	-0.49	0.70	0.01	-0.30
Housing Unit Proximity	0.12	0.84	0.06	0.30
Job Proximity	-0.32	0.84	-0.06	-0.27
Housing Unit to Job Proximity	-0.06	0.94	0.05	0.12
Exposure of Jobs to Housing Units*	0.18	0.01	0.93	-0.11
Exposure of Housing Units to Jobs*	0.24	0.05	0.92	0.08
Nuclearity	-0.13	0.34	0.07	0.61

**Notes:** Extraction method = principal-components analysis; rotation method = Varimax. \* Variable was log transformed.

Although there is always some potential for misleading simplifications with factor labels, we label the four factors as follows:

- **Intensity:** all three of the density indices and the continuity index loaded highly on this factor, as did the job concentration index (negatively); after rotation, this factor accounted for 26 percent of the total variance in 1990 and 25 percent of the variance in 2000.
- **Compactness:** both centrality indices and the three proximity indices loaded highly on this factor; accounting for 25 percent of the total variance in 1990 and 30 percent of the variance in 2000.
- **Mixing:** housing concentration and both mixed land-use indices loaded highly on this factor; after rotation, this factor accounted for 21 percent of the total variance in 1990 and 22 percent of the

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variance in 2000.

- **Core-dominance:** the mono-nuclearity index loaded highly on this factor; accounting for 8 percent of the total variance in 1990 and 7 percent of the variance in 2000.

**Table 5.** Exploratory Factor Analysis Results for 2000

	Component			
<b>Summary Statistics</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
Initial Eigenvalue	4.93	4.51	1.48	0.82
Percent of Variance Explained	35.00	32.00	11.00	6.00
Rotation Eigenvalue	4.16	3.49	3.13	0.96
Percent of Variance Explained	30.00	25.00	22.00	7.00
<b>Rotated Factor Loadings</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
Housing Density*	-0.05	0.79	0.56	-0.06
Job Density*	0.06	0.73	0.61	-0.06
Peripheral Density	-0.17	0.88	0.16	0.01
Continuity	-0.04	0.87	0.10	-0.21
Housing Concentration	0.23	-0.13	0.80	-0.07
Job Concentration	0.33	-0.66	0.11	-0.30
Housing Centrality	0.74	-0.17	0.30	0.09
Job Centrality	0.80	-0.31	0.06	0.07
Housing Unit Proximity	0.91	0.06	0.12	0.13
Job Proximity	0.93	-0.10	-0.07	0.10
Housing Unit to Job Proximity	0.97	-0.01	0.05	0.11
Exposure of Jobs to Housing Units*	-0.01	0.32	0.90	0.07
Exposure of Housing Units to Jobs*	0.09	0.27	0.91	0.06
Nuclearity	0.37	-0.12	0.05	0.87

**Notes:** Extraction method = principal-components analysis; rotation method = Varimax. \* Variable was log transformed.

With the exception of concentration, the housing and jobs metrics for each dimension loaded together on the factors; the density metrics loaded together; the centrality and proximity metrics loaded together; and the mixed-use metrics loaded together. These results contrast to some degree from what we found in our exploratory work with 50 metropolitan areas [redacted], indicating that a larger and more diverse sample reveals more regularity in metropolitan spatial structure than we found with a smaller

sample of only large metropolitan areas. Table 6 depicts the highest and lowest scoring EUAs on each factor for 2000. We explore the factor analysis results in more detail in the companion paper in this issue.

**Table 6.** Highest and lowest ranking EUAs across four factors, 2000

Rank <sup>#</sup>	Intensity	Compactness	Mixing	Core-Dominance
1	Jersey City, NJ	Bloomington--Normal, IL	New York, NY	Waterbury, CT
2	Fort Lauderdale, FL	Fargo--Moorhead, ND-MN	San Francisco, CA	Great Falls, MT
3	Orange County, CA	Grand Forks, ND-MN	Honolulu, HI	Jersey City, NJ
4	Los Angeles--Long Beach, CA	Sioux Falls, SD	State College, PA	Joplin, MO
5	Miami, FL	Bakersfield, CA	Jersey City, NJ	Dover, DE
6	San Jose, CA	Santa Fe, NM	Washington, DC-MD-VA-WV	Lancaster, PA
7	Bergen--Passaic, NJ	Tuscaloosa, AL	Newark, NJ	Casper, WY
8	West Palm Beach--Boca Raton, FL	Dubuque, IA	Boston, MA-NH	Bridgeport, CT
9	Nassau--Suffolk, NY	Lynchburg, VA	Madison, WI	Jackson, MS
10	Detroit, MI	Lawton, OK	Atlantic--Cape May, NJ	Stamford--Norwalk, CT
...				
248	York, PA	Portsmouth--Rochester, NH-ME	Pensacola, FL	Huntsville, AL
249	Altoona, PA	New London--Norwich, CT-RI	Lynchburg, VA	Gary, IN
250	Portland, ME	Ventura, CA	Johnson City--Kingsport--Bristol, TN-VA	Detroit, MI
251	Williamsport-PA	Galveston--Texas City, TX	Clarksville--Hopkinsville, TN-KY	Fayetteville--Springdale--Rogers, AR
252	Portsmouth--Rochester, NH-ME	Salinas, CA	Gadsden, AL	Biloxi--Gulfport--Pascagoula, MS
253	Lewiston--Auburn, ME	Visalia--Tulare--Porterville, CA	Goldsboro, NC	Vallejo--Fairfield--Napa, CA
254	Wheeling, WV-OH	Monmouth--Ocean, NJ	Jacksonville, NC	Ventura, CA
255	Bellingham, WA	Atlantic--Cape May, NJ	Hickory--Morganton--Lenoir, NC	Brazoria, TX
256	State College, PA	Brazoria, TX	Anniston, AL	Dallas, TX
257	Reading, PA	Jersey City, NJ	Ocala, FL	Grand Rapids--Muskegon--Holand, MI

**Notes:** N=257; # 1 = highest scoring (least sprawling); 257 = lowest scoring (most sprawling).

The factor analysis confirms that measures of metropolitan density

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explain the most variation within the sample for 1990, but that density alone is insufficient to properly characterize metropolitan spatial structure. If metropolitan density truly is the best metric of metropolitan land use patterns, we should see fewer factors and more indices loading heavily on the intensity factor in both years. Instead, three additional factors help to summarize the underlying structure in the data and that are unrelated to density: compactness, mixing, and core-dominance. The compactness factor also is more important than intensity in explaining variation within the sample in 2000.

The density, continuity, and job concentration indices all appear to measure one underlying facet of metropolitan land use patterns that we associate with development intensity and the overall amount of activity within the EUA. What is interesting is the sign on the factor loading for the job concentration metric; job concentration is inversely associated with the factor (and the density and continuity indices). Thus, metropolitan areas with lower concentrations of employment generally had higher overall employment and housing densities, and higher intensity. Jersey City, NJ and Fort Lauderdale, FL typify this sort of area, in which employment is distributed throughout the region with very low concentration, even while overall employment and housing densities are high. The most intensively-developed EUAs tended to have large populations, be located on coasts, and be part of larger urban agglomerations where development pressures are high. The least-intensive EUAs include many small regional job centers in the northeast, including Reading, PA and Portland, ME. Thus, land use patterns may diverge as areas grow and mature, both densifying and deconcentrating over time. It is also possible that job concentration is serving to proxy for industrial composition of the area (Berry and Horton, 1970), and thus EUAs with distinctive industrial mixes may exhibit distinct spatial patterns, a hypothesis that we will explore in our companion paper.

The compactness factor appears to measure the spatial orientation of housing and jobs within the metropolitan area, with higher scoring EUAs having more centralized and more proximate development than lower scoring EUAs. Many of the most compact EUAs are located in inland locations with small to mid-sized populations and have not yet been subsumed within larger urban agglomerations. Examples include Bloomington-Normal, IN; Sioux Falls, SD; and Santa Fe, NM. By contrast, the least-compact EUAs tend to be located along the coasts and within

large urbanized regions, such as Atlantic City-Cape May, NJ, Galveston-Texas City, TX, and Portsmouth-Rochester, NH. The reduced compactness in PMSAs may occur as both housing and employment markets extend into the interstitial space between PMSAs and their larger urbanized region.

The factor analysis confirms that land use mixing appears as a distinctive dimension of metropolitan land use patterns in the U.S. Higher scoring EUAs on this factor tend to have strong downtowns with high concentrations of both housing and jobs, such as New York, San Francisco, Honolulu, Washington, and Boston EUAs. Many of these high scoring EUAs are located in coastal areas and in larger urban agglomerations. Mixing tends to be substantially higher in the western and northeastern U.S. than in the midwest and south. Nearly all of the lowest scoring EUAs are located in the southeastern U.S., with very low mixing in Ocala, FL, Anniston, AL, and Jacksonville, NC EUAs. Mixing also tends to be highest in the metropolitan areas with the oldest central cities such as New York, Philadelphia, Baltimore, Boston, and New Orleans, and lowest in metropolitan areas where their central cities only recently reached a population of 50,000 residents.

Our measure of mono-nuclearity (here, the share of an EUA's jobs within centers that are located in the core center) is unrelated to the other land use indices but does help to explain variation in land use patterns not otherwise explained by the intensity, mixing, or compactness. We see that the EUAs with the smallest populations in our sample tend to score high on the core-dominance factor, indicating that most if not all of their employment within centers was located in their one historic core center in 2000. Examples here include Great Falls, MT, Joplin, MO, and Casper, WY. Several larger EUAs (most often in the Northeastern U.S.) also scored high on core-dominance, including Jersey City, NJ, and Bridgeport, CT. By contrast, several EUAs score low on the core-dominance factor, indicating the presence of multiple job centers that compete with the historic core. Examples here include Grand Rapids, MI; Dallas, TX; and Ventura, CA.

It is beyond the scope of this paper to probe the origins of the inter-regional differences in metropolitan land-use patterns we have identified here. Suffice it to note that no one region of the country outperforms on all land-use dimensions, on average. In the extreme case, the Northeast has EUAs with the lowest levels of intensity and compactness, but the highest levels of mixing and core-dominance, on average. Yet, the



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Northeast also has some of the oldest and most central cities in our sample, which developed under a development paradigm that differs markedly from the post-war paradigm in place when many southern and western central cities developed (Borchert, 1967; Leven, 1978). We explore this aspect further in our companion paper. The differing vintage and character of metropolitan development suggests that national policies aimed at changing one particular dimension of land use (i.e., density) may produce disparate regional consequences that must be carefully considered (Fulton et al., 2001).

One final aspect of the factor analysis is worth mentioning. Despite seemingly similar results, our methodology is distinctly different from the methodology used to generate the four sprawl indices of Ewing et al. (2002). We employed all 14 of our indices in one exploratory factor analysis, generating four uncorrelated factors that summarize metropolitan land use patterns. The Ewing et al. (2002) methodology used separate factor analyses to generate summary scores on four preconceived dimensions: residential density, mixed-use, centeredness, and street connectivity. As a result, their methodology produced factors that are strongly inter-correlated (especially the density and street connectivity factors) and “appear to represent a similar dimension” (Jaret et al., 2009, p.74). Here, we produce unique factors that better represent the multidimensionality of metropolitan land use patterns and that can be used in subsequent analyses without introducing redundancy in the explanatory variables.<sup>17</sup> Our analysis also includes a larger dataset that uses appropriately bounded urban geographies for measuring sprawl and is more representative of metropolitan land use patterns within the United States. We note also that our land use metrics are intentionally measured independent of the transportation network upon which residents and businesses depend for day-to-day interactions.

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<sup>17</sup> Comparing our factor scores to the sprawl scores reported by Ewing et al. (2002) for 81 metropolitan areas with reported data from both datasets, we find that our compactness factor is moderately correlated with their centeredness factor ( $r=0.55$ ); our intensity factor is moderately correlated with their street connectivity and mixed-use factors ( $r=0.54$  and  $r=0.56$ , respectively), and with their mixed-use factor ( $r=0.36$ ); our mixing factor is well correlated with their residential density factor ( $r=0.77$ ) and street connectivity factor ( $r=0.51$ ), less well correlated with their mixed-use factor ( $r=0.37$ ) and with their centeredness factor ( $r=0.29$ ); and that our core-dominance factor is modestly correlated with their centeredness and mixed-use factors ( $r=0.34$  and  $r=0.30$ , respectively). Thus, it is clear that our factors are measuring quite different things than theirs, even when similar labels might imply that we are measuring the same underlying dimension of land use.

## Conclusion And Future Research

Over the last decade it has become accepted practice to view metropolitan land use patterns as having multiple dimensions, but less work has been done in developing measures for these dimensions and investigating the degree to which these dimensions are empirically independent and have changed over time. We contribute by investigating in a descriptive fashion the spatial patterns of residential and non-residential land use for 257 U.S. metropolitan areas in 1990 and 2000 with 14 indices measuring both job and housing locations (defined for Census 2000 boundaries). The analysis here includes the largest sample of U.S. “extended urban areas” to date that have been studied with multi-dimensional land use metrics, allowing a more comprehensive and nuanced view of land use patterns and their evolution over time.

We found that, though U.S. EUAs got denser in both housing and employment during the 1990s, by every other measure they developed in more “sprawl-like” patterns, on average. The most substantial changes in land use patterns occurred in the realm of job concentration, proximity, and centralization. Our exploratory factor analysis revealed that four factors were the most appropriate and parsimonious way for summarizing the dimensions of housing and employment land uses in both 1990 and 2000. This factorial ecology of U.S. EUAs demonstrated remarkable stability. Substantial differences in mean factor scores emerged by population size, coastal location, metropolitan type, and region of the country, though no one group was associated with “more sprawl” across all dimensions. More “mature” EUAs evinced higher intensity and land use mixing, but lower compactness and core-dominance, on average.

The major empirical takeaway from our exploration is the significant alteration of the geography of metropolitan employment during the 1990s. By far the largest changes in our land use metrics occurred in the realms of employment. Jobs became more prevalent per unit of geographic area, but they also became less spatially concentrated and further from the historical urban core, on average. Moreover, the inter-metropolitan differences in spatial patterns of housing and employment became less distinct over the decade. We speculate that this may be due to the narrowing of inter-metropolitan economic specialization associated with deindustrialization and a more generalized transformation into service-oriented local economies.

In a broader sense, this paper reinforced the growing consensus concerning the multi-dimensional and dynamic nature of metropolitan land use patterns. Our results imply that analysis of both the causes and consequences of land use patterns must take a nuanced approach that examines multiple dimensions explicitly. Our results confirm that “anti-sprawl” programs must be carefully constructed based on the particular land use dimension that is seen as causing the most detrimental outcomes. Alternatively, “anti-sprawl” policies and planning activities applied universally are likely to produce disparate impacts depending on region, metropolitan scale, type, and location.

In the next article, we explore metropolitan land use typologies using cluster analysis of our factor scores, revealing some interesting variation by metropolitan geographic, historical, economic, and demographic characteristics. Future research will build upon the foundation established in these two papers. We will undertake a series of multivariate analyses aimed at revealing the causes and consequences of evolving dimensions of U.S. metropolitan land use patterns, with more attention paid to evaluating land use patterns according to the vintage and maturity of metropolitan areas. We also will update the analysis once the 2010 employment and commuting data become available at the small-area geographies required for this analysis, enabling a longer-term evaluation of metropolitan land use change.

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## **Appendix 1. Method for Allocation of Census Block Group Population and Housing Information to Raster Grid Cells**

Our previous work identified ice, water, and wetlands as three classes of land cover that should be excluded as “undevelopable” land for the purposes of measuring land use patterns (citation redacted). Here, we clipped each block group boundary to its “developable” land area using data on surface water and wetlands from the U.S. Geological Survey (USGS), as of 2001. The surface water data layer includes oceans, bays, lakes, reservoirs, rivers, canals, streams, glaciers, and swamp or marsh areas. We then apportioned the population and housing unit counts for each block group to the 500m x 500m raster grid cells, assuming that population or housing were equally distributed across cells within the clipped block groups. The point here is to avoid apportioning population or housing units to grid cells that are covered predominately by water or wetlands, where presumably the population is unlikely to live. We employed a two-step process to ensure sufficient coverage. We first apportioned the population and housing attributes to grid cells based on the block group with the majority land area within the grid cell. For missed block groups, we apportioned their population and housing counts to the grid cell containing the centroid of the block group. We then added the population counts from the two steps. The process ensured we obtained population and housing counts for the majority of block groups within the MSA. Unfortunately, the process still missed some of the population or housing units within low-density block groups, in which less than 1 person or housing unit would be apportioned to each cell crossing the block group. In most cases, the missed population or housing units from low-density block groups comprised less than five percent of the MSA totals for each year.

## **Appendix 2. Method of Allocation of Job Information to Raster Grid Cells**

Place-of-work data were reported at various geographies for 1990, including census blocks, census tracts, traffic analysis zones (TAZs), and where smaller area data were not available, counties. We constructed complete boundary layers for study areas based on the appropriate geographic levels for the available place-of-work data. In some cases, place-of-work data were reported using multiple levels (such as from block groups in one county and from TAZs in an adjacent county), requiring a patchwork approach that merged the place-of-work data layers. The place-of-work data layers were then clipped by the surface water layer and apportioned as described above for population and housing, so as to ensure that worker counts were allocated to “developable” land areas.

An important and troubling problem with such a patchwork process is that the spatial apportionment of place-of-work data to cells happens differentially depending on the source boundaries. For instance, census block groups are smaller than census tracts. Thus, worker data available at the block group level may be concentrated in only part of the census tract. As a result, our apportionment approach will more closely resemble reality for metropolitan areas with worker data available at the block group level than for metropolitan areas with worker data available only at the census tract level. In many cases, TAZs are smaller than census tracts and thus worker apportionment in metropolitan areas with data available at the TAZ level will also be more accurate than for metropolitan areas with data available at the tract level. Often, place-of-work data are available only at the county level for outer counties within the MSAs in 1990. Typically, the apportionment approach misses these outer county workers entirely because their small number is spread too thin over a large geography. Overall, core areas of the MSAs tend to have good worker coverage while outer areas may have minimal coverage. Such a problem also arises with the population and housing-unit data from low-density block groups.

A related problem emerges when we compared the change in apportionment from 1990 to 2000, which in some places were performed using different geographies. In these places, changes in the concentration of jobs may happen because of actual changes in where jobs were located or because of changing source boundaries. In addition, the boundaries for

even the same units, such as census tracts, change to some extent each Decennial Census. (Place-of work-data are not available at normalized geographies, unlike the population and housing count data.) The problem with spatial analysis using inconsistent unit boundaries has been frequently acknowledged and discussed (Fotheringham and Wong, 1991; Horner and Murray, 2002).



### Appendix 3. Formulae for Computing Land Use Indices

#### Nomenclature

Let

$i$  = a particular type of land use or spatially based observation, in our case, either residential use (for which we use the number of housing units located there) or nonresidential use (for which we use the number of employees who work there).

$s$  = denotation of the smallest spatial scale area used in the analysis; grid cells equaling one-tenth of a square mile (a square with sides of 500 meters each);  $1, 2, \dots, s, \dots, S$ .

$u$  = denotation of the largest spatial scale area used in this analysis; the extended urban area (EUA). [for definition of EUA see Wolman et al. (2005)]

$S$  = the number of grid cells in EUA  $u$ .

$T(i)s$  = the number of observations of land use  $i$  (dwellings or jobs) in grid cell  $s$  (that is also within  $u$ ).

$T(j)s$  = the number of observations of land use  $j$  (dwellings or jobs) in grid cell  $s$  (that is also within  $u$ ).

$T(i)u$  = the total number of observations (dwellings or jobs) of land use  $i$  in EUA  $u$ .

$As$  = the area in grid cell  $s$ ; 500 meters x 500 meters or 0.0965 square miles.

$Au$  = the total area in EUA  $u$ ; calculated as:  $\sum_{s=1}^S As$ .

$P$  = the number of grid cells in EUA  $u$  that are classified as the Urbanized Area (UA) by the U.S. Census Bureau.

$o$  = a grid cell containing the city hall of the largest municipality in the EUA, which we assume represents the historic center of the EUA and part of the central business district (CBD).

$d[s,o]$  = the distance between the centroids of generic grid cell  $s$  and grid cell  $o$ .

$d[m,k]$  = the distance between the centroids of generic grid cell  $m$  and grid cell  $k$ .

$c$  = a grid cell that meets the selection criterion for inclusion in a jobs

center, as described below; 1, 2, ...,  $c$ , ...,  $C$ .

$g$  = a grid cell that meets the selection criterion for inclusion in a jobs center and that is located within a contiguous group of cells including cell  $o$ , which we specify as the CBD.

### Dimensions and Metrics

Note: these metrics are scaled such that higher values indicate that the EUA is less “sprawling” for that dimension.

**Density** the degree to which the EUA  $u$  is intensively developed; measured separately for the  $i$ th land use (housing units or jobs).

$$DENS(i)u = \frac{T(i)u}{Au} = \frac{\sum T(i)s}{\sum As} \quad (1)$$

**Peripheral Density** the degree to which the EUA has been developed (for any urban use) in an unbroken fashion; measured as the share of the EUA that is classified as in the Urbanized Area, using the 2000 UA criteria of the Census. This metric does not distinguish land uses and was termed macro-continuity in previous work.

$$PDENSu = \frac{P}{S} \text{ (range: 0-1)} \quad (2)$$

**Mix** the degree to which housing units and jobs are located in the same grid cell, on average, across the EUA; measured separately as exposure of jobs-to-housing and housing-to-jobs.

$$MIX(i, j)u = \sum \left[ \left( \frac{T(i)s}{T(i)u} \right) * T(j)s \right] \quad (3)$$

**Concentration** the degree to which housing units and jobs are located disproportionately in a few cells within the EUA; measured separately for housing units and for jobs. The index indicates the proportion of housing units or jobs that would need to shift cells in order to achieve an even distribution across all the grid cells in the EUA. It is similar to a dissimilarity index but, instead of two land uses being compared, each is compared to the share of the total EUA area located within the cell.

$$CONC(i)u = \frac{1}{2} \sum \left| \frac{T(i)s}{T(i)u} - \frac{As}{Au} \right| \text{ (range: 0-1)} \quad (4)$$

**Centrality** The degree to which housing units and jobs are located nearer to the historic core of the EUA. We defined the core of the EUA as the location of city hall(s) of the major municipality for each

metropolitan area. We measured the distance between the city hall point in cell  $o$  and each grid cell centroid in the EUA, weighted by the number of housing units or jobs in each cell. Some EUAs contained two or more historic city halls and thus the distance for each grid cell was computed to the nearest city hall. We standardized this weighted average distance by the average distance to city hall from the grid cells comprising the EUA, so as not to inevitably specify larger EUAs as less centralized.

$$ENT(i)u = \frac{\frac{1}{S} \sum d_{s,o}}{\sum (d_{s,o} * \frac{T(i)s}{T(i)u})} \quad (5)$$

$$d_{s,o} = \sqrt{(lat_s - lat_o)^2 + (long_s - long_o)^2} \quad (6)$$

where,

$lat_s$  = latitude for the centroid of grid cell  $s$ .

$long_s$  = longitude for the centroid of grid cell  $s$ .

$lat_o$  = latitude for the centroid of grid cell  $o$ , where the city hall was located.

$long_o$  = longitude for the centroid of grid cell  $o$ , where the city hall was located.

**Proximity** the degree to which housing units, jobs, or housing unit/job combinations are close to each other across the EUA, relative to the land area of the EUA. We standardized the proximity index in analogous manner as centrality. For feasibility of computing proximity we aggregated information to one-square mile grid cells.

The weighted average distance between different land uses  $i$  and  $j$  in two randomly chosen grid cells  $m$  and  $k$  in the EUA  $u$  can be expressed as (with  $d$  defined as above in (6) ):

$$DIST(i,j)u = \sum_{m=1}^S \sum_{k=1}^S d_{m,k} \left[ \frac{T(j)k}{T(j)u} \right] \left[ \frac{T(i)m}{T(i)u} \right] \quad (7)$$

Analogously, the weighted average distance between the same land use  $j$  in two randomly chosen grid cells  $m$  and  $k$  in the EUA  $u$  can be expressed as (with an analogous expression for use  $i$ ):

$$DIST(j,j)u = \sum_{m=1}^S \sum_{k=1}^S d_{m,k} \frac{[T(j)k * T(j)m]}{(T(j)u)^2} \quad (8)$$

It makes sense to standardize these distance measures (as with centrality), inasmuch as larger-area EUAs will tautologically have greater average distances between any pair of land uses. For this standardization, we

compute the average distance between centroids of the S grid cells:

$$DISTu = \sum_{m=1}^S \sum_{k=1}^S \frac{d_{m,k}}{S} \quad (9)$$

From the above terms, we can express three alternative measures of proximity: intra-use, inter-use, and weighted average across both uses

$$PROXj = \frac{DISTu}{DIST(j,j)u} - 1 \quad (10)$$

$$PROXij = \frac{DISTu}{DIST(i,j)u} - 1 \quad (11)$$

$$PROXu = \frac{DISTu[T(i)u+T(j)u]}{T(i)u[DIST(i,i)u]+T(j)u[DIST(j,j)u]} - 1 \quad (12)$$

**Core-Dominated Nuclearity** the degree to which jobs within an EUA are disproportionately located within the core center  $g$ , as opposed to distributed across sub-centers  $c$  within the EUA. Grid cells considered centers, either at the core or outside the core, are those whose jobs density (measured as the number of jobs located within 1-square mile from the grid cell's centroid) are at least four (4) standard deviations above the mean for the given EUA  $u$ . The core center includes but is not limited to cell  $o$ , the one containing the city hall of the largest municipality defining the EUA.  $NUCLu = \frac{\sum T(j)g}{\sum T(j)c}$  (13) (range: 0-1)